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(71) Applicant: **THE CHARLES STARK DRAPER LABORATORY, INC.** [US/US]; 555 Technology Square, Cambridge, MA 02139 (US).

(72) Inventors: **WEINBERG, Marc, S.**; 119 Broad Meadow Road, Needham, MA 02492 (US). **KOUREPENIS, Anthony, S.**; 31 Lawsbrook Road, Acton, MA 01720 (US). **SAWYER, William, D.**; 8 Carville Avenue, Lexington, MA 02421 (US). **BORENSTEIN, Jeffrey, T.**; 936 Highland Street, Holliston, MA 01746 (US). **CONNELLY, James, H.**; 67 Kathleen Road, Weymouth, MA 02190 (US). **DUWEL, Amy, E.**; 10 Cowperthwaite Street, Cambridge, MA 02138 (US). **LENTO, Christopher, M.**; 91 Marginal Street, Boston, MA 02128 (US). **COUSENS, James, R.**; 52 Cranberry Road, Hanson, MA 02341 (US).

(74) Agents: **THOMPKINS, Thomas, E., Jr.** et al.; Iandiorio & Teska, 260 Bear Hill Road, Waltham, MA 02451-1018 (US).

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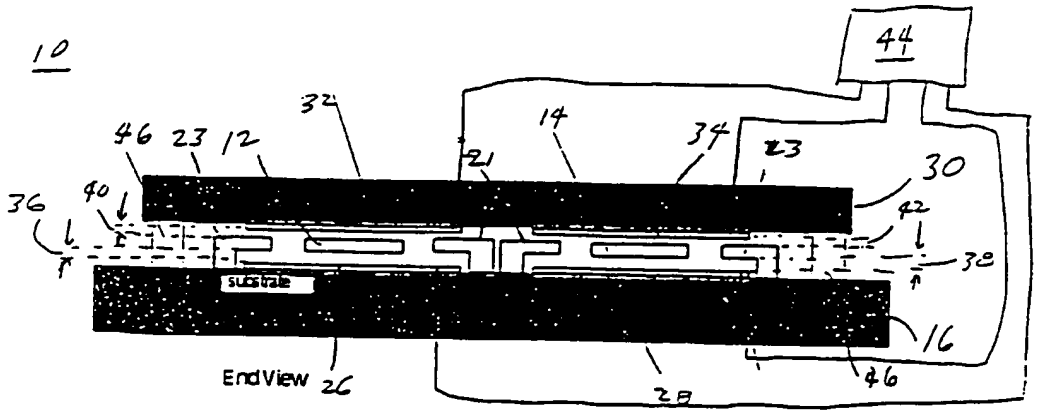
(54) Title: TUNING FORK GYROSCOPE



(57) Abstract: A tuning fork gyroscope typically including at least one proof mass with an upper sense plate disposed above the proof mass and a lower sense plate disposed below the proof mass and means for sensing changes in the nominal gaps between the sense plate and the proof mass and for outputting a signal indicative of the gyroscope angular rate.

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TUNING FORK GYROSCOPE

FIELD OF THE INVENTION

This invention relates to a tuning fork gyroscope.

RELATED APPLICATIONS

This application is a Continuation-in-Part of Serial No. 10/004,145 filed October 23, 2001 entitled METHOD OF ANODICALLY BONDING A MULTI-LAYER DEVICE WITH A FREE MASS and is incorporated herein by reference. This application also claims priority from Provisional Application Serial No. 60/327,450 filed October 5, 2001, and Provisional Application Serial No. 60/327,434 filed on October 5, 2001.

BACKGROUND OF THE INVENTION

Tuning fork gyroscopes are used to sense angular displacement in military and commercial (e.g., automotive) environments. In one design, two silicon proof masses (vibrating elements) are suspended above a silicon or glass substrate (or a glass substrate with a silicon layer thereon) and there is a conductive (e.g., metal) sense plate (electrode) on the substrate under each proof mass. The inner and outer edges of each proof mass include combs or electrode fingers. Between the proof masses and adjacent to the outer edge of each proof mass are drive motors and sensors with complementary combs or electrode fingers interleaved with the combs of the two proof masses for oscillating the

errors. First, because of tolerance induced construction asymmetries, the left and right drive axis forces will not be equal so that a differential proof mass motion ensues. A second error ensues because of the contact potential (also known as work function) between the metal conductors and the silicon parts. The contact potential adds roughly 0.25 V to the voltage potential between both sense plates and the proof masses. Thus, the common mode motion induced by drive to sense force coupling causes a current flow from the proof mass. This current is interpreted as a bias error.

Generally, increasing the voltage applied to the sense plates increases the scale factor of these instruments. However, this voltage increase is limited by an effect known as snap down. The applied voltage causes electrostatic forces, which act as a negative spring. For the conventional single-sided design, the forces pull the proof mass toward the sense plate, further increasing the negative spring. At sufficiently high voltages, the negative electrostatic spring overcomes the mechanical stiffness and the proof mass unstably snaps into the sense plates. A voltage that is a fraction, typically 1/3 to 2/3 of the snap down voltage, excites the sense plates.

In general then, the asymmetrical design of the prior art tuning fork gyroscopes with sense plates disposed only under the proof masses has been used successfully in many applications. For additional applications, however, still higher scale factor, lower bias error, better bias stability, and lower sensitivity to linear acceleration are required.

BRIEF SUMMARY OF THE INVENTION

It is therefore an object of this invention to provide a tuning fork gyroscope which

defining a first nominal gap between the first proof mass and the first sense plate, the second sense plate disposed under the second proof mass defining a second nominal gap between the second proof mass and the second sense plate. A second substrate is spaced from the first substrate and supports at least third and fourth sense plates. The third sense plate is disposed over the first proof mass defining a third nominal gap between the first proof mass and the third sense plate, and the fourth sense plate is disposed over the second proof mass defining a fourth nominal gap between the second proof mass and the fourth sense plate. Means for sensing changes in the nominal gaps between each sense plate and each proof mass provides an output signal indicative of the gyroscope's angular rate about an axis parallel to the substrates.

In a preferred embodiment, the means for sensing includes a first voltage, V_b, with $+V_b$ applied to the first sense plate and $-V_b$ applied to the second sense plate, and a second voltage, V_t, different from but approximately equal to the first voltage, applied to the third and fourth sense plates, with $-V_t$ applied to the third sense plate and $+V_t$ applied to the fourth sense plate. The first and second nominal gaps may be equal to g_b and the third and fourth nominal gaps may be equal to g_t. The ratio of the second and first voltages may be a function of the ratio of nominal gap g_t and nominal gap g_b, preferably, $V_t/V_b = g_t^3/g_b^3$.

In another embodiment, the means for sensing may include a first voltage, V_{bl}, applied to the first sense plate, a second voltage, V_{br}, applied to the second sense plate, a third voltage, V_{tl}, applied to the third sense plate and a fourth voltage, V_{tr}, applied to the fourth sense plate. The first nominal gap may be g_{bl}, the second nominal gap may be g_{br},

fourth sense plate. The first nominal gap may be g_{bl}, the second nominal gap may be g_{br}, the third nominal gap may be g_{tl}, and the fourth nominal gap may be g_{tr}. The weighted summation of the output currents on each of the sense plates may be I_{sum}, where

$$I_{sum} = I_{tr} - I_{tl}\left(\frac{g_{tl}}{g_{tr}}\right)^3 + I_{bl}\left(\frac{g_{bl}}{g_{tr}}\right)^3 - I_{br}\left(\frac{g_{br}}{g_{tr}}\right)^3$$ and where I_{sum} is proportional to the input angular rate and does not depend on vertical displacement.

This invention also features a method for reducing errors in a tuning fork gyroscope including determining a first distance, g_t, between an upper sense plate and a proof mass and a second distance, g_b, between a lower sense plate and the proof mass, and applying a first voltage, V_t, to the upper sense plate and a second voltage, V_b, to the lower sense plate, wherein the ratio of the first voltage and the second voltage is a function of the first distance and the second distance. The first and second voltages may be DC voltages, or they may be AC carrier excitation voltages. In one example, $V_t/V_b = g_t^3/g_b^3$. The step of determining the first and second distances may include measuring the capacitance between the upper sense plate and the proof mass and the capacitance between the lower sense plate and the proof mass, respectively.

This invention also features a method for reducing errors in a tuning fork gyroscope including first and second proof masses, a left upper sense plate disposed over the first proof mass, a right upper sense plate disposed over the second proof mass, a left lower sense plate disposed under the first proof mass and a right lower sense plate disposed under the second proof mass, including measuring a first distance, g_{tl}, between the left upper sense plate and the first proof mass, a second distance, g_{tr}, between the right

equal to g_t. The ratio of the second voltage V_t and first voltage V_b may be a function of the ratio of the second nominal gap g_t and the first nominal gap g_b, for example,

$$\frac{V_t}{V_b} = \frac{g_t^3}{g_b^3}.$$

This invention also features a method for fabricating a tuning fork gyroscope with upper and lower sense plates, including providing a silicon substrate, etching the silicon substrate to provide at least one recess in the silicon substrate, producing a structure layer having a predetermined thickness, etching the structure layer to provide at least two proof masses, and applying a metal coating to the silicon substrate beneath a portion of each proof mass. The method of fabricating further includes providing a glass substrate, etching the glass substrate to provide at least one recess in the glass substrate, depositing a multimetal layer to the at least one recess, depositing a multimetal layer to the at least one recess, electrostatically bonding the silicon substrate to the glass substrate, and etching the silicon substrate down to the structure layer. The method may include the further step of applying KOH thinning prior to etching the silicon substrate. Producing the structure layer may include diffusing boron onto a surface of the silicon substrate or it may include growing epitaxial silicon with boron onto a surface of the silicon substrate. Diffusing boron onto a surface of the silicon substrate may include diffusing boron-geranium silicon or silicon-on-insulator to define structural thickness. Boron may be diffused into a silicon substrate to define structural thickness.

The proof masses may have a thickness in the range of 5 to 100 μm. The multimetal layer may be chosen from the group consisting of Ti/Pt/Au and Ti/Pt.

A second substrate is spaced from the first substrate and supports at least third and fourth sense plates. The third sense plate may be disposed adjacent the first proof mass but opposite the first sense plate, defining a third nominal gap between the first proof mass and the third sense plate. The fourth sense plate may be disposed adjacent the second proof mass but opposite the second sense plate defining a fourth nominal gap between the second proof mass and the fourth sense plate. Means for sensing changes in the nominal gaps between each sense plate and each proof mass provides an output signal indicative of the gyroscope's angular rate about an axis perpindicular to the substrates.

In a preferred embodiment, the means for sensing includes a first voltage, V_b, with $+V_b$ applied to the first sense plate and $-V_b$ applied to the second sense plate, and a second voltage, V_t, different from but approximately equal to the first voltage, applied to the third and fourth sense plates, with $-V_t$ applied to the third sense plate and $+V_t$ applied to the fourth sense plate. The first and second nominal gaps may be equal to g_b and the third and fourth nominal gaps may be equal to g_t. The ratio of the second V_t and first V_b voltages is a function of the ratio of the nominal gap g_t and the nominal gap g_b, preferably $\frac{V_t}{V_b} = \frac{g_t^3}{g_b^3}$.

In another embodiment, the means for sensing may include a first voltage, V_{bl}, applied to the first sense plate, a second voltage, V_{br}, applied to the second sense plate, a third voltage, V_{tl}, applied to the third sense plate, and a fourth voltage, V_{tr}, applied to the fourth sense plate. The first nominal gap may be g_{bl}, the second nominal gap may be g_{br}, the third nominal gap may be g_{tl} and the fourth nominal gap may be g_{tr}. The ratio of the

Fig. 5 is a flow chart depicting the primary steps of another method of reducing errors in a tuning fork gyroscope according to the subject invention;

Fig. 6A is a top schematic view of the proof mass structure and the first or lower substrate of a tuning fork gyroscope in accordance with the present invention having vertical sense plates;

Fig. 6B is a top schematic view of the proof mass structure and the first or lower substrate of a tuning fork gyroscope in accordance with the present invention having vertical sense plates arranged as combs;

Fig. 7 is a cross-sectional schematic view of another embodiment of a tuning fork gyroscope according to the present invention having a single proof mass; and

Figs. 8A-8G are cross-sectional schematic drawings depicting the method of manufacturing the tuning fork gyroscope of the subject invention.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Prior art tuning fork gyroscope 300, Fig. 1, is also known in the art as a comb drive gyroscope. Gyroscope 300 includes vibrating or proof masses 302 and 303. Interleaved fingers 304, including outer comb drive fingers 306, 307 and inner comb driven fingers 308, 309 impart vibrational motion to vibrating masses 302, 303. The sensed motion is wired to electronics (not shown) that generate the driving voltage so that a self-oscillator is realized. It is known to reverse the role of inner and outer combs. Both solid and horizontally and vertically split inner combs have been used although horizontal splits in both the inner and outer combs are now preferred. Vibrating masses 302, 303 are

state acceleration causes only small offset or bias errors which do not depend on the input rate because these low frequency variations in gap are not at the drive frequency. Such errors are rejected during demodulation. Also, steady state acceleration causes common displacement of the proof masses while the desired angular rate inputs cause differential motion. Thus, gyroscopes with sense electrodes only on one side of the proof masses – typically below -- as shown in Fig. 1, result in scale factor error.

Also, gyroscopes with sense electrodes only below the proof masses result in bias errors caused by forces along the drive axis 332 that result from the motor drive, a principal source of bias errors in known tuning fork gyroscope designs. Such bias errors can be significant depending on the construction tolerances to which the gyroscopes are made. As noted in the Background section above, both the left and right outer motors exert forces in opposite directions and lift forces tend to cancel out, but the motor drive to sense axis coupling still causes two types of bias errors. The left and right sense axis forces will not be equal so that a differential proof mass motion ensues, because of tolerance induced construction asymmetries. A second error ensues because the contact potential between the metal conductors and the silicon parts causes common mode vertical motion to be sensed as an erroneous angular rate.

Upper sense plate tuning fork gyroscope 10 in accordance with the present invention, Figs. 2A and 3, typically includes first and second proof masses 12, 14 which are suspended with respect to first substrate 16. Comb drives 18, 20 provide means for oscillating proof masses 12, 14 along a drive axis, shown by vector 22. First and second sense plates 26, 28 are disposed under first and second proof masses 12, 14, respectively,

angular displacement of the gyroscope. Support posts 46 may also be conductive so that the electrical connections from third and fourth sense plates 32, 34 to the first substrate 16 may be accomplished.

In operation, excitation source 44 may apply a first voltage, V_t, with $+V_t$ applied to sense plate 34 and $-V_t$ applied to sense plate 32, and a second voltage, V_b, different from but approximately equal to V_t, with $+V_b$ applied to sense plate 26 and $-V_b$ applied to sense plate 28. The motion generated current, which flows through the proof masses 12, 14, indicates differential proof mass motion in the sense direction. If the applied voltage is DC, a single modulation is required to obtain the estimated angular rate from the proof mass current. If an AC carrier is applied, two levels of demodulation are needed.

The advantages of the increased symmetrical design of tuning fork gyroscope 10 of this invention include: reducing scale factor sensitivity to acceleration; increasing the scale factor; reducing the bias errors; and improving the stability of the gyroscope. Moreover, sense plates 32, 34 and substrate 30 also act as a dust cover, protecting proof masses 12, 14 from contamination, and they shield inner drive combs 21 from stray electric fields emanating from outer combs 23.

With upper 32, 34 sense plates and lower 26, 28 sense plates, the scale factor is more than doubled. This results from the increased symmetry of the sense plate design. In prior art gyroscopes such as shown in Fig. 1, increasing the sense plate voltage results in the proof masses being drawn toward the sense plates. Because of the increased symmetry of gyroscope 10, Figs. 2A, 2B and 3, the proof masses do not move as the sense plate voltages are increased. The upper sense plates increase the total plate area and

and lower sense plates and the proof masses. When the upper left and upper right gaps are equal, and the lower left and lower right gaps are equal, measuring the gaps, step 102, Fig. 4, obtains a first distance, g_t, between the upper sense plates and the proof masses and a second distance, g_b, between the lower sense plates and the proof masses. These as-constructed gaps may be obtained, for example, by measuring the capacitance between the upper sense plates and the proof masses and between the lower sense plates and the proof masses.

Applying voltages to the upper and lower sense plates, step 104, includes applying a first voltage, V_t, to the upper sense plate and a second voltage, V_b, to the lower sense plate. The ratio of the first voltage, V_t, and the second voltage, V_b, is a function of the first and second distances, g_t and g_b. Voltages V_t and V_b may be DC voltages. The invention can be extended to AC carrier excitation where two modulation steps are used--the first for the carrier frequency and the second for the drive frequencies. Preferably, in all embodiments of the present invention having more than one proof mass, positive voltages are applied to the upper right and lower left sense plates and negative voltages are applied to the upper left and lower right sense plates. This arrangement leads to the proof mass current representing the differential displacement and, hence, angular rate.

Nominal gaps 36, 38 may be equal to g_b and nominal gaps 40, 42 may be equal to g_t. To eliminate the scale factor sensitivity to sense axis linear acceleration, the ratio of voltages V_t and V_b is preferably a function of the ratio of the nominal gap g_t and nominal gap g_b. In one example, where g_t is not equal to g_b, the ratio is:

$$V_t/V_b = g_t^3/g_b^3. \qquad (1)$$

The Taylor expansion for the scale factor (B) becomes.

$$\frac{\Delta SF / SF}{\Delta y / g} = \frac{3\Delta g}{g}$$

When the upper and lower gaps are equal ($\Delta g=0$) and the upper and lower voltage absolute values are equal, the scale factor does not change with displacements caused by acceleration (Δy). If the proof mass is displaced up 0.1μm during construction, $\Delta g/g=0.2\mu m/3\mu m$ and the scale factor variation is 0.15 $\Delta y/g$. With only one sense plate, the scale factor variation is $2\Delta y/g$.

In another example, as shown in step 202, Fig. 5, the distance, g_{tl}, between the left upper sense plate 32 and the first proof mass 12 is measured, as is the distance, g_{tr}, between the right upper sense plate 34 and the second proof mass 14; the distance, g_{bl}, between the left lower sense plate 26 and the first proof mass 12; and the distance, g_{br}, between the right lower sense plate 28 and the second proof mass 14. In step 204 voltage V_t is applied to the left upper sense plate, voltage - V_t to the right upper sense plate; voltage -V_b is applied to the left lower sense plate; and voltage V_b is applied to the right lower sense plate, when $g_{tl} = g_{tr} = g_t$ and $g_{bl} = g_{br} = g_b$. In this instance, the ratio of V_t and V_b is that as shown by equation (1).

For the case where g_{tl} is not equal to g_{tr} and g_{bl} is not equal to g_{br}, step 206, the voltage applied to the upper left sense plate is V_{tl}, the voltage applied to the upper right sense plate is V_{tr}, the voltage applied to the lower left sense plate is V_{bl} and the voltage applied to the lower right sense plate is V_{br}. In this example, excitation source 44 may apply a different voltage to each sense plate 26, 28, 32 and 34, Fig. 3, i.e., V_{bl} to sense

Also, it is known that one voltage may be applied to the proof masses and the currents that appear on the sense plates may be read. In accordance with the present invention, one voltage may be applied to the proof masses 12, 14, Fig. 3 and the output currents I_{bl}, I_{br}, I_{tl}, and I_{tr} of four sense plates 26, 28, 32 and 34 may be read by sensing means 45, Fig. 2. In this example, nominal gap 36 is g_{bl}, nominal gap 38 is g_{br}, nominal gap 40 is g_{tl}, and nominal gap 42 is g_{tr}. The weighted summation of output currents on each of the sense plates is I_{sum} where

$$I_{sum} = I_{tr} - I_{tl}\left(\frac{g_{tl}}{g_{tr}}\right)^3 + I_{bl}\left(\frac{g_{bl}}{g_{tr}}\right)^3 - I_{br}\left(\frac{g_{br}}{g_{tr}}\right)^3. \qquad (4)$$

I_{sum} in equation (4) is proportional to the input angular rate and does not depend on vertical displacement.

Also, it will be apparent to those skilled in the art that the gyroscope of this invention may be used to sense in-plane rotations, or to sense out-of-plane rotations, with one example of the latter described in U.S. Patent No. 6,257,059 B1 to Weinberg et al. For the tuning fork gyroscope in accordance with this invention used to sense in-plane motion, as described above and in Fig. 2A, sense plates 26, 28, 32 and 34 are driven in the same plane as drive axis 22, and the sense axis for proof masses 12, 14 is into and out of the page, perpendicular to drive axis 22. For sensing out-of-plane motion, sense plates 26', 28', 32', 34', Fig. 6A, are perpendicular to the plane of drive axis 22' and the sense axis displacement for proof masses 12', 14' is in the direction of arrows 100, 101. Nominal gaps 36', 38' may be equal to g_{bl} and g_{br}, nominal gaps 40', 42' may be equal to g_{tl} and g_{tr} in equations (2) and (3). In another embodiment, numerous sense plates, which

Processing starts with lightly doped silicon wafer or substrate 220, Fig. 8A that contains a 5 to 50 micron thick highly doped epitaxial layer 221. A recess 222 is etched into the silicon. This recess defines the gap spacing of the conducting plates. The etching may be accomplished using, for example, plasma enhanced ion etching.

The epitaxial layer 221 defines the part thickness. A structure layer 224, Fig. 8B is etched to provide at least one proof mass 250 and may be 5 to 100 μm in thickness, with a thickness of 5 to 20 μm preferred. Silcon-on-insulator or boron-geranium-silicon may be used for thicker, 10 to 100 μm thick, proof masses. The features of the structure and of the connecting posts 225 between the lower and upper plates are defined by reactive ion etching (RIE), Fig. 8C. The posts 225 also serve as electrical connections between the plates. By etching past the p++ etch stop, the structures are released. A CF_3Br or SF_6 chemistry may be used for the etching in a parallel plate reactor or inductively-coupled plasma, which gives straight sidewalls and high aspect ratios.

The glass processing involves forming recesses 226, 228, Fig. 8D, in glass substrate 230. Recesses 226, 228 are approximately 1700 Å deep. Glass substrate 230 may be a borosilicate glass, such as Corning 7740. Then multimetal pads 232, 234 are deposited in recesses 226, 228. Multimetal pads 232, 234 may be Ti/Pt/Au or Ti/Pt. Multimetal pads 232, 234 are deposited such that multimetal pads protrude only 500 Å above the surface of the glass substrate 230. The multimetal pads 232, 234 form the capacitor sense plates and the leads to and from the transducer.

Silicon substrate 220 and glass substrate 230 are then electrostatically bonded together, Fig. 8E. The electrostatic bonding takes place at approximately 335°C with a

plates on opposite sides of a proof mass.

Although specific features of the invention are shown in some drawings and not in others, this is for convenience only as each feature may be combined with any or all of the other features in accordance with the invention. The words "including", "comprising", "having", and "with" as used herein are to be interpreted broadly and comprehensively and are not limited to any physical interconnection. Moreover, any embodiments disclosed in the subject application are not to be taken as the only possible embodiments.

Other embodiments will occur to those skilled in the art and are within the following claims:

What is claimed is:

2. The tuning fork gyroscope of claim 1 in which the means for sensing includes a first voltage, V_b, with $+V_b$ applied to the first sense plate and $-V_b$ applied to the second sense plate, and a second voltage, V_t, different from but approximately equal to the first voltage V_b, with $-V_t$ applied to the third sense plate and $+V_t$ applied to the fourth sense plate.

3. The tuning fork gyroscope of claim 2 in which the first and second nominal gaps are equal to g_b and the third and fourth nominal gaps are equal to g_t.

4. The tuning fork gyroscope of claim 3 in which the ratio of the second V_t and first V_b voltages is a function of the ratio of the nominal gap g_t and the nominal gap g_b.

5. The tuning fork gyroscope of claim 4 in which:

$$\frac{V_t}{V_b} = \frac{g_t^3}{g_b^3}$$

6. The tuning fork gyroscope of claim 1 in which the means for sensing includes a first voltage, V_{bl}, applied to the first sense plate, a second voltage, V_{br}, applied to the second sense plate, a third voltage, V_{tl}, applied to the third sense plate, and a fourth voltage, V_{tr}, applied to the fourth sense plate.

13. The tuning fork gyroscope of claim 12 wherein the motor combs are vertically split.

14. The tuning fork gyroscope of claim 12 wherein the motor combs are horizontally split.

15. The tuning fork gyroscope of claim 12 further including guard bands for controlling out-of-plane sensitivities.

16. The tuning fork gyroscope of claim 1 wherein the sense plates are made of metal.

17. The tuning fork gyroscope of claim 1 wherein the sense plates are made of deposited silicon.

18. The tuning fork gyroscope of claim 1 including a torsion beam connecting an anchor to a base beam.

19. The tuning fork gyroscope of claim 18 wherein the torsion beam is a folded beam.

26. The tuning fork gyroscope of claim 25 in which I_{bl} is the output current that appears on the first sense plate, I_{br} is the output current that appears on the second sense plate, I_{tl} is the output current that appears on the third sense plate, and I_{tr} is the output current that appears on the fourth sense plate.

27. The tuning fork gyroscope of claim 26 in which the first nominal gap is g_{bl}, the second nominal gap is g_{br}, the third nominal gap is g_{tl}, the fourth nominal gap is g_{tr}.

28. The tuning fork gyroscope of claim 27 in which the weighted summation of output currents on each of the sense plates is I_{sum}.

29. The tuning fork gyroscope of claim 28 where

$$I_{sum} = I_{tr} - I_{tl}\left(\frac{g_{tl}}{g_{tr}}\right)^3 + I_{bl}\left(\frac{g_{bl}}{g_{tr}}\right)^3 - I_{br}\left(\frac{g_{br}}{g_{tr}}\right)^3 .$$

30. The tuning fork gyroscope of claim 29 where I_{sum} is proportional to input angular rate.

31. A method for reducing errors in a tuning fork gyroscope comprising:

determining a first distance, g_t, between an upper sense plate and a proof mass and a second distance, g_b, between a lower sense plate and the proof mass; and

upper sense plate disposed over the second proof mass, a left lower sense plate disposed under the first proof mass and a right lower sense plate disposed under the second proof mass, the method comprising:

measuring a first distance, g_{tl}, between the left upper sense plate and the first proof mass, measuring a second distance, g_{tr}, between the right upper sense plate and the second proof mass, measuring a third distance, g_{bl}, between the left lower sense plate and the first proof mass, and measuring a fourth distance, g_{br}, between the right lower sense plate and the second proof mass; and

applying a first voltage, V_{tl}, to the left upper sense plate, a second voltage, V_{tr}, to the right upper sense plate, a third voltage, V_{bl}, to the left lower sense plate, and a fourth voltage, V_{br}, to the lower right sense plate,

wherein the ratio of V_{tl} and V_{bl} is a function of g_{tl} and g_{bl} and the ratio of V_{tr} and V_{br} is a function of g_{tr} and g_{br}.

38. The method of claim 37 wherein V_{tl} is not equal to V_{tr} and V_{bl} is not equal to V_{br}, and wherein

$$\frac{V_{tl}}{V_{bl}} = \frac{g_{tl}^{3}}{g_{bl}^{3}} \text{ and } \frac{V_{tr}}{V_{br}} = \frac{g_{tr}^{3}}{g_{br}^{3}}.$$

39. The method of claim 38 in which the voltages V_{tr} and V_{bl} are of opposite sign than the voltages V_{tl} and V_{br}.

equal to g_b and the second nominal gap is equal to g_t.

43. The tuning fork gyroscope of claim 40 in which the ratio of the second voltage V_t and first voltage V_b is a function of the ratio of the second nominal gap g_t and the first nominal gap g_b.

44. The tuning fork gyroscope of claim 40 in which $\frac{V_t}{V_b} = \frac{g_t^3}{g_b^3}$.

45. A method for fabricating a tuning fork gyroscope with upper and lower sense plates, the method comprising:

providing a silicon substrate;

etching the silicon substrate to provide at least one recess in the silicon substrate;

producing a structure layer having a predetermined thickness;

etching the structure layer to provide at least one proof mass;

applying a metal coating to the silicon substrate beneath a portion of each proof mass;

providing a glass substrate;

etching the glass substrate to provide at least one recess in the glass substrate;

depositing a multimetal layer to the at least one recess;

52. The method of claim 48 including the further step of applying KOH thinning prior to etching the silicon substrate.

53. The method of claim 48 in which diffusing boron onto a surface of the silicon substrate includes diffusing silicon-on-insulator to define structural thickness.

54. The method of claim 45 wherein the silicon substrate includes a lightly doped layer and a highly doped epitaxial layer.

55. The method of claim 54 wherein the thickness of said highly doped epitaxial layer is between 5 and 100 μm thick.

56. The method of claim 45 wherein the etching of the silicon subtrate is plasma enhanced ion etching.

57. The method of claim 45 wherein the structure layer is 5 to 100 μm thick.

58. The method of claim 45 wherein the structure layer is 5 to 20 μm thick.

59. The method of claim 45 wherein connecting posts between the silicon substrate and the glass substrate are defined by reactive ion etching.

direction of the plane of the first substrate;

at least first and second sense plates supported by the first substrate, the first sense plate disposed adjacent the first proof mass defining a first nominal gap between the first proof mass and the first sense plate, the second sense plate disposed adjacent the second proof mass defining a second nominal gap between the second proof mass and the second sense plate;

a second substrate spaced from the first substrate;

at least third and fourth sense plates supported by the second substrate, the third sense plate disposed adjacent the first proof mass but opposite the first sense plate, defining a third nominal gap between the first proof mass and the third sense plate, the fourth sense plate disposed adjacent the second proof mass but opposite the second sense plate, defining a fourth nominal gap between the second proof mass and the fourth sense plate; and

means for sensing changes in the first, second, third and fourth nominal gaps between each sense plate and each proof mass and for outputting a signal indicative of the gyroscope angular rate about an axis perpendicular to the substrates.

64. The tuning fork gyroscope of claim 63 in which the means for sensing includes a first voltage, V_b, with $+V_b$ applied to the first sense plate and $-V_b$ applied to the second sense plate, and a second voltage, V_t, different from but approximately equal to the first voltage V_b, with $-V_t$ applied to the third sense plate and $+V_t$ applied to the fourth sense plate.

third voltages is a function of the ratio of the first and third nominal gaps and the ratio of the second and third voltages is a function of the ratio of the second and fourth nominal gaps.

71. The tuning fork gyroscope of claim 70 in which:

$$\frac{V_{tl}}{V_{bl}} = \frac{g_{tl}^{\ 3}}{g_{bl}^{\ 3}} \text{ and } \frac{V_{tr}}{V_{br}} = \frac{g_{tr}^{\ 3}}{g_{br}^{\ 3}}.$$

72. The tuning fork gyroscope of claim 71 in which the voltages V_{tr} and V_{bl} are of opposite sign than the voltages V_{tl} and V_{br}.

73. The tuning fork gyroscope of claim 72 in which the voltages V_{tr} and V_{bl} are positive voltages and the voltages V_{tl} and V_{br} are negative voltages.

74. The tuning fork gyroscope of claim 63 including additional sense plates arranged in a comb-like configuration.

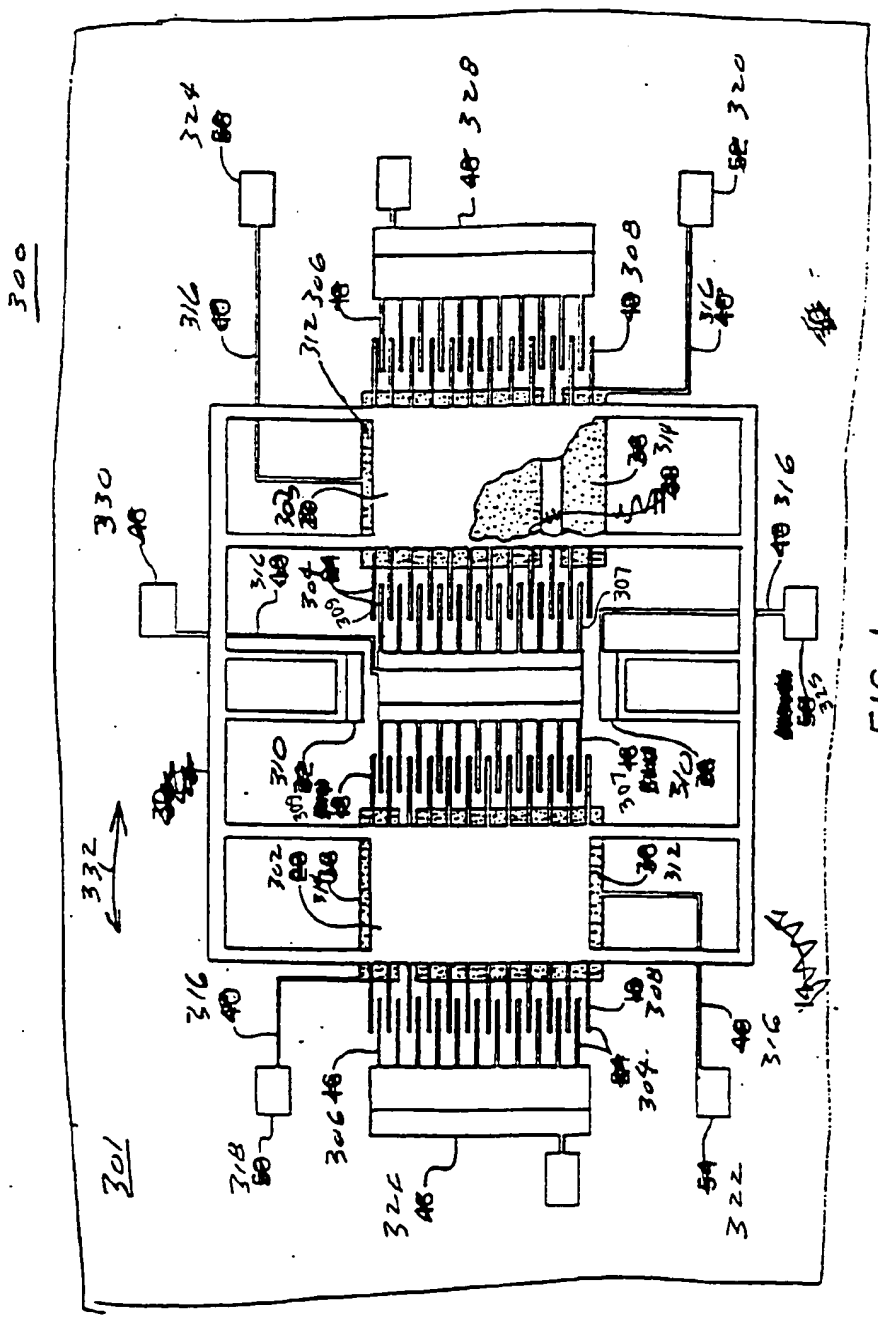

FIG. 1
PRIOR ART

INVENTION RECORD (Page 7)

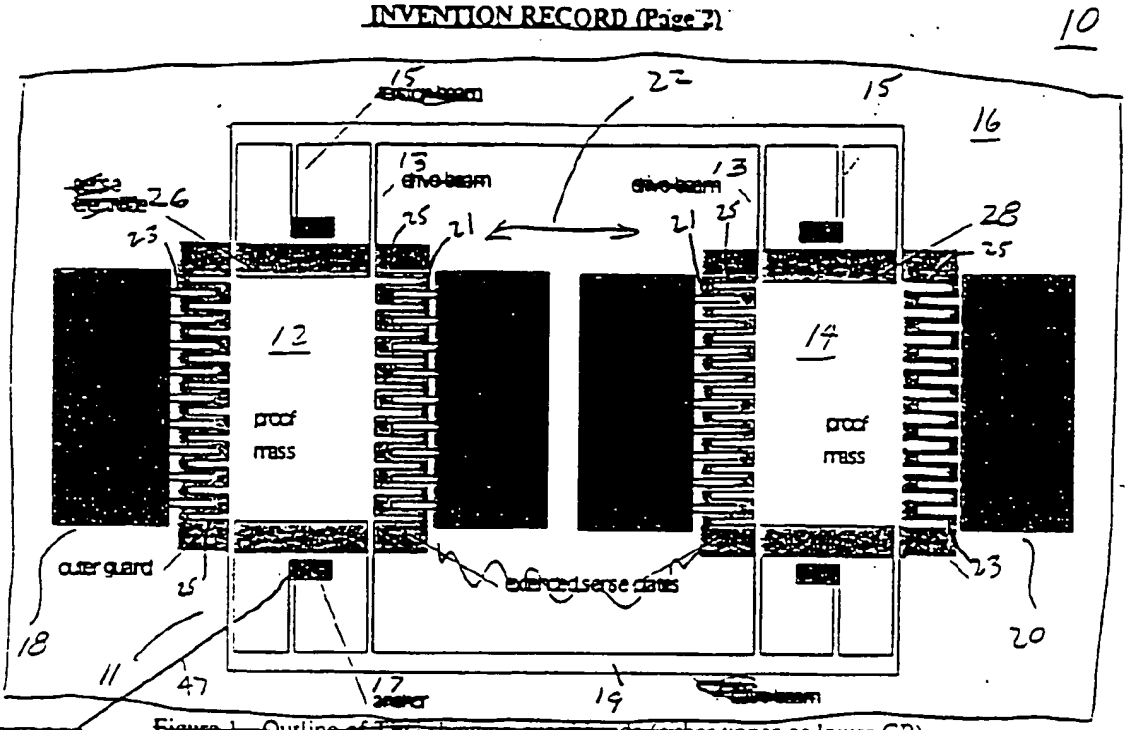

Figure 1. Outline of TFG showing guard bands (either upper or lower GB)

FIG. 2A

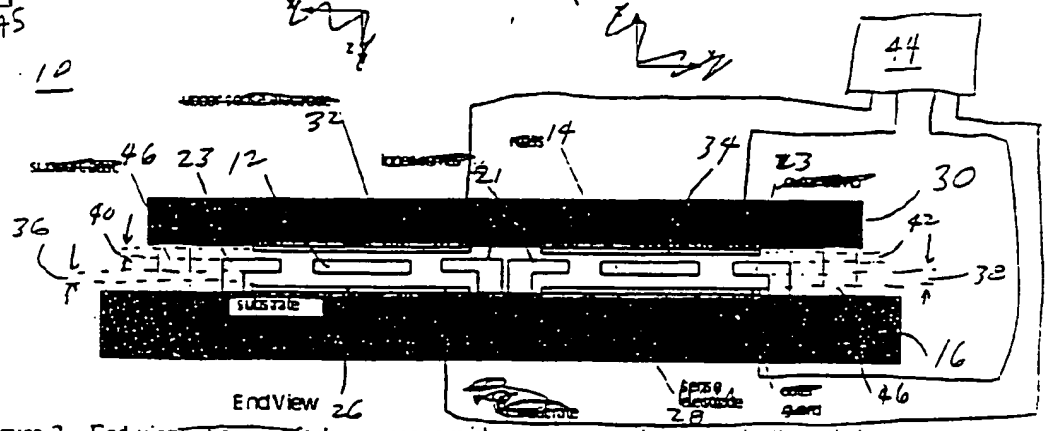

Figure 2. End view of tuning fork gyroscope with upper sense plates, vertically split inner combs, and sense plates extending under and over inner combs.

FIG. 3

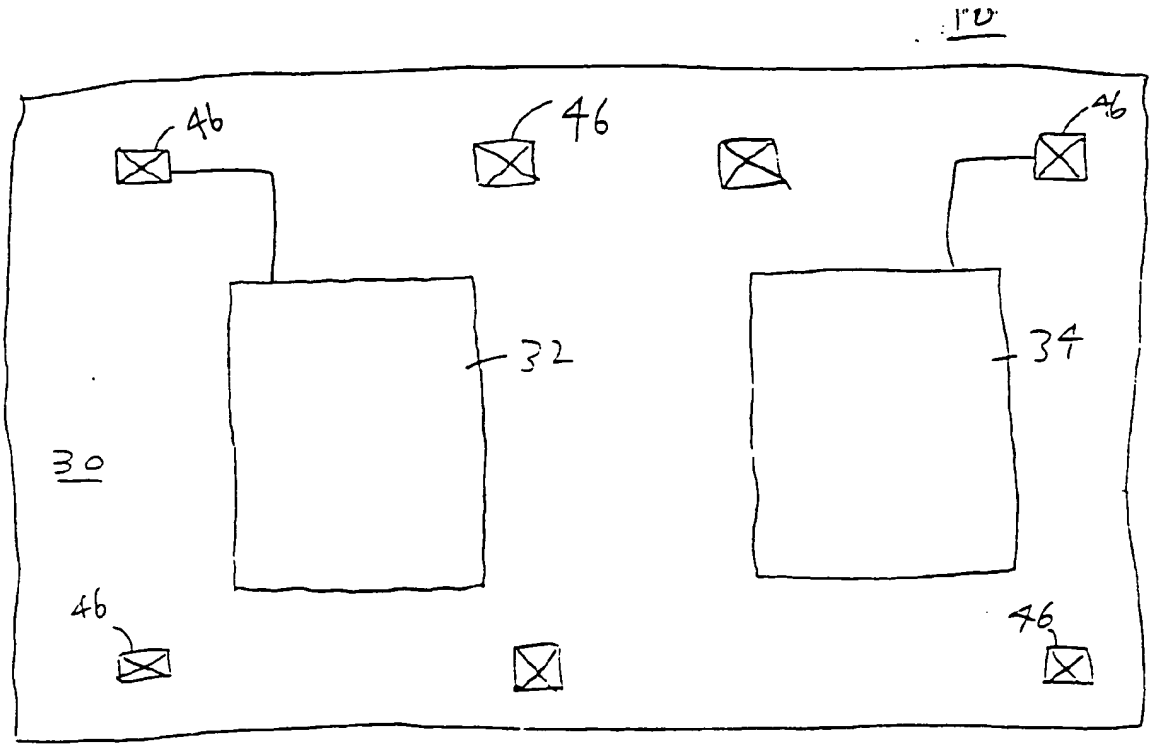

Fig. 2B

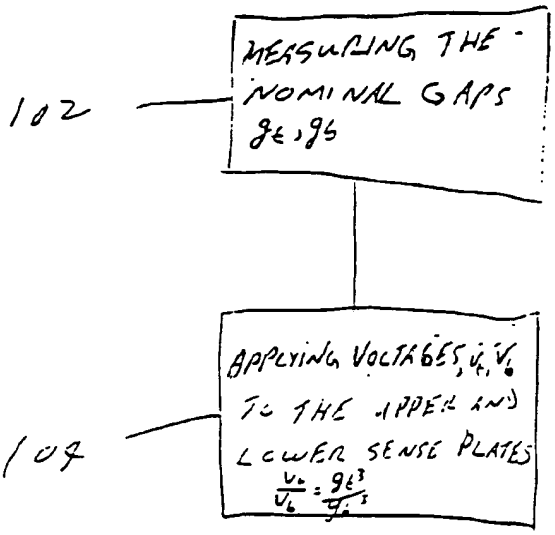
102
MEASURING THE NOMINAL GAPS g_t, g_b
104
APPLYING VOLTAGES V_t, V_b TO THE UPPER AND LOWER SENSE PLATES
$\frac{V_t}{V_b} = \frac{g_t^3}{g_b^3}$

FIG. 4

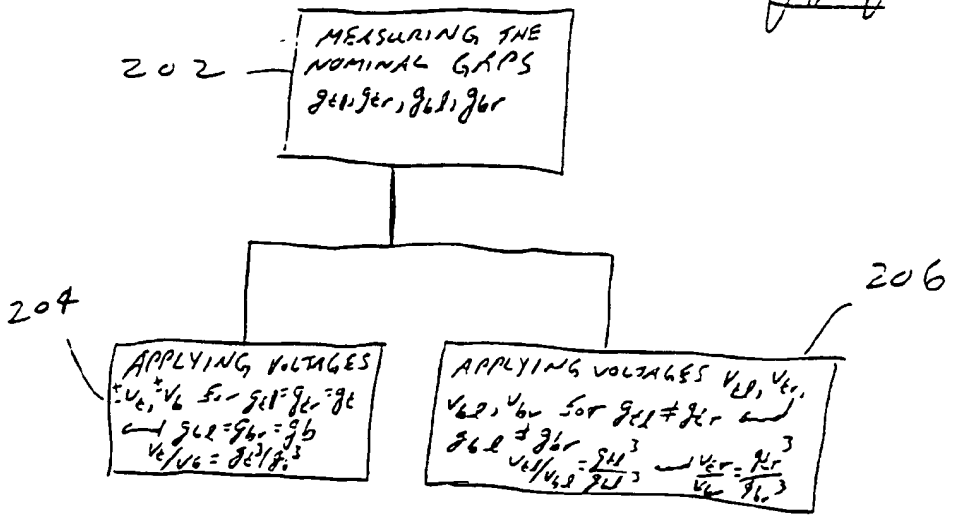
202
MEASURING THE NOMINAL GAPS $g_{tl}, g_{tr}, g_{bl}, g_{br}$
204
APPLYING VOLTAGES $\pm V_t, \pm V_b$ SO $g_{tl} = g_{tr} = g_t$
$g_{bl} = g_{br} = g_b$
$V_t/V_b = g_t^3/g_b^3$
206
APPLYING VOLTAGES $V_{tl}, V_{tr}, V_{bl}, V_{br}$ SO $g_{tl} \neq g_{tr}$
$g_{bl} \neq g_{br}$
$\frac{V_{tl}}{V_{bl}} = \frac{g_{tl}^3}{g_{bl}^3}$ $\frac{V_{tr}}{V_{br}} = \frac{g_{tr}^3}{g_{br}^3}$

FIG. 5

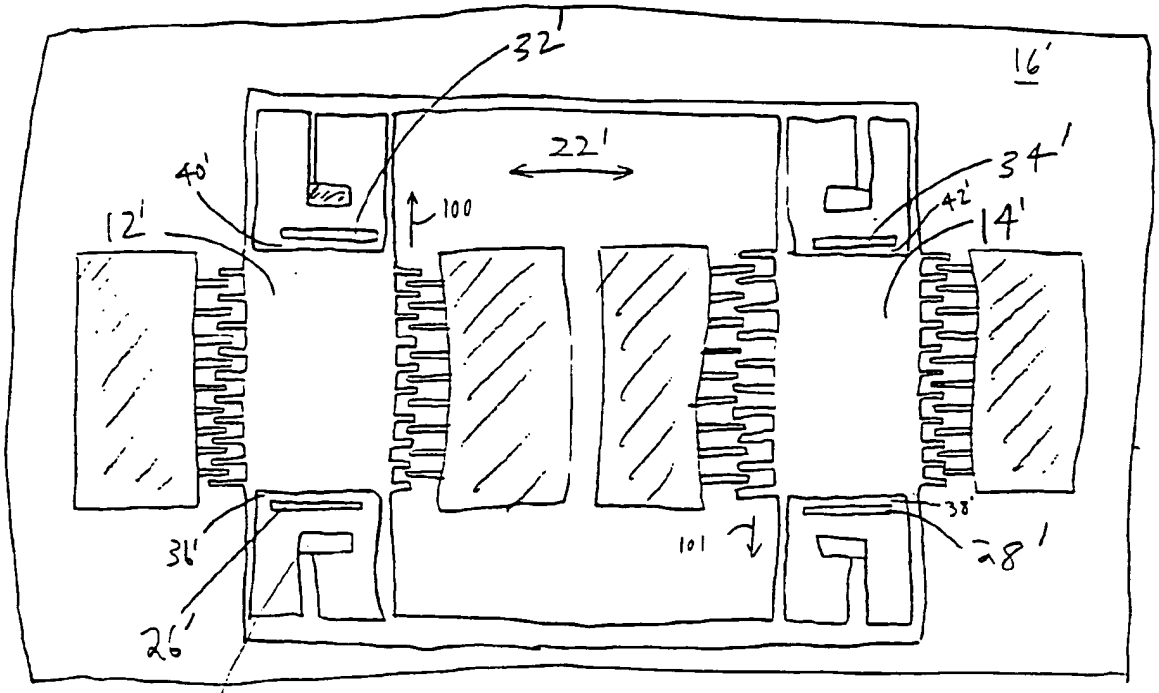

FIG. 6A

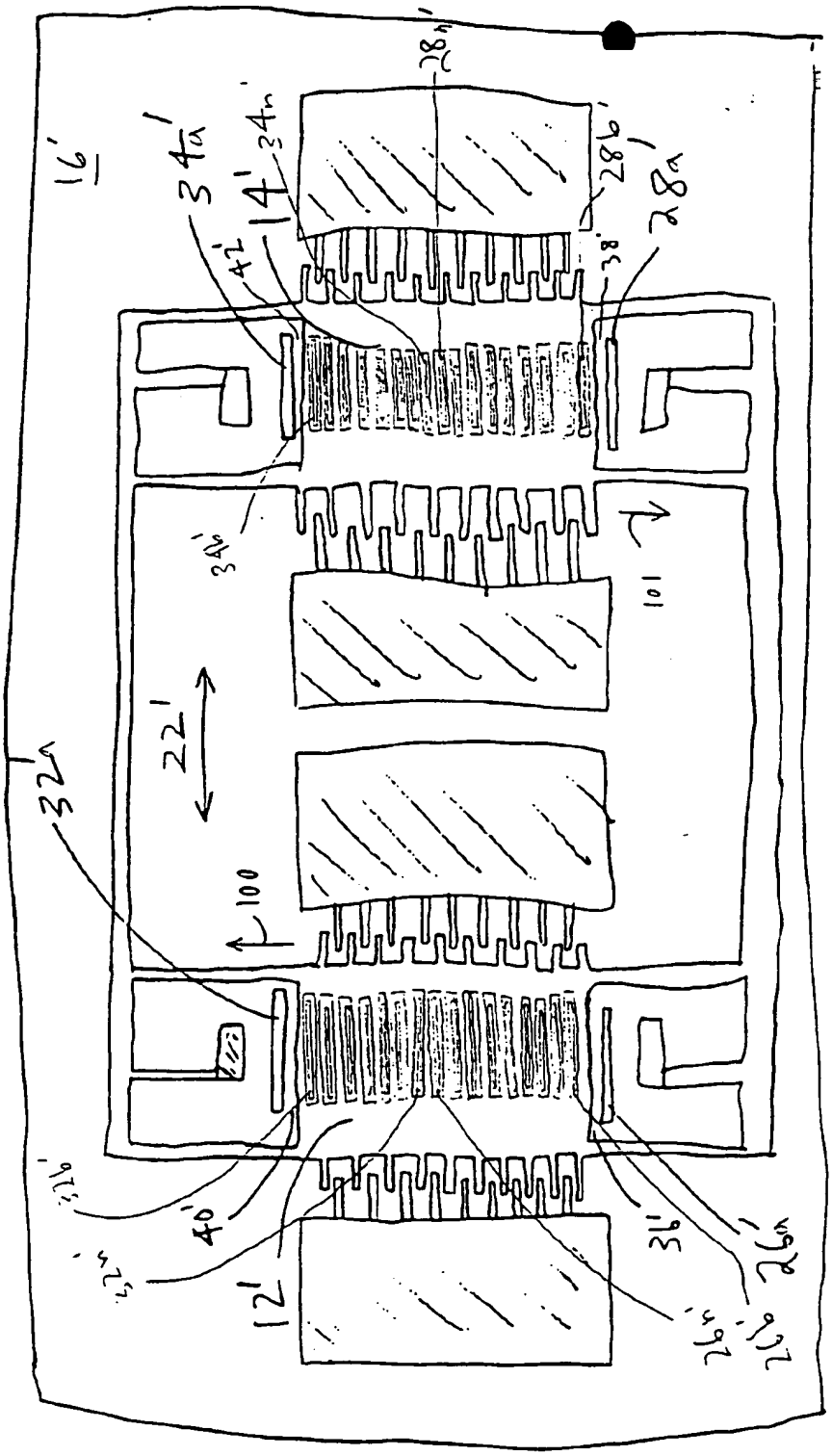

FIG. 6B

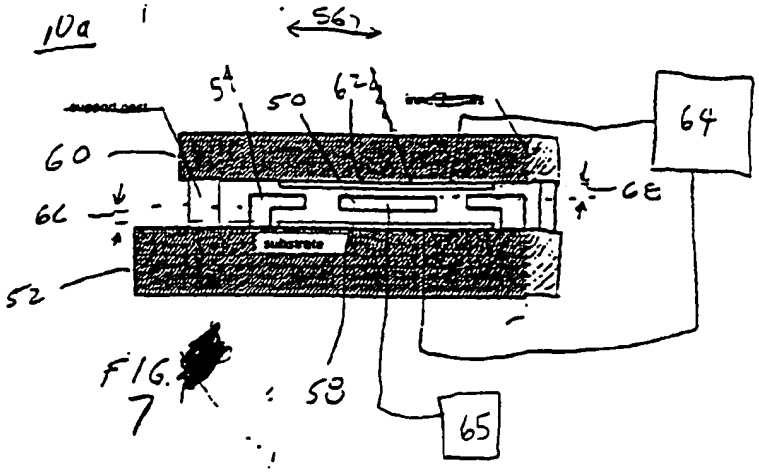

FIG. 7

FIG. 8A

FIG. 8B

FIG 8C

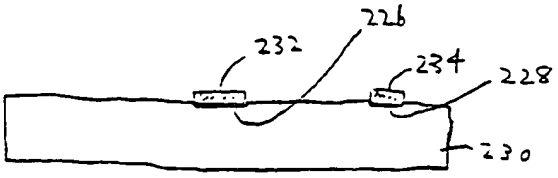

FIG. 8D

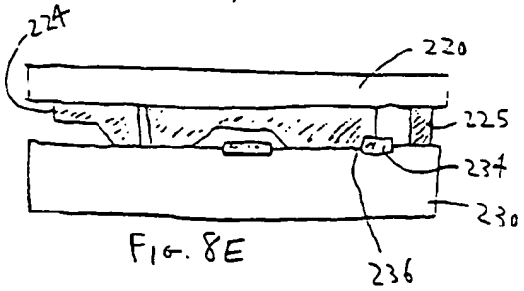

FIG. 8E

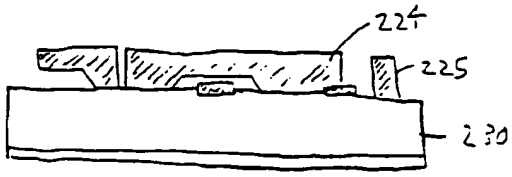

FIG. 8F

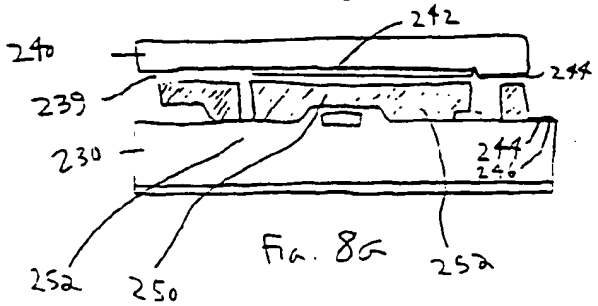

FIG. 8G

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